MEASURING THE DIRECTIONALITY OF COUPLING:
PHASE VERSUS STATE SPACE DYNAMICS AND
APPLICATION TO EEG TIME SERIES

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Measuring the directionality of coupling between dynamical systems is one of the challenging problems
in nonlinear time series analysis. We investigate the relative merit of two approaches to assess direction-
ality, one based on phase dynamics modeling and one based on state space topography. We analyze
unidirectionally coupled model systems to investigate the ability of the two approaches to detect driver-
responder relationships and discuss certain problems and pitfalls. In addition we apply both approaches
to the intracranial electroencephalogram (EEG) recorded from one epilepsy patient during the seizure-
free interval to demonstrate the general suitability of directionality measures to reflect the pathological
interaction of the epileptic focus with other brain areas.

Keywords: Synchronization; directionality; EEG, epilepsy; time series analysis.

1. Introduction

When investigating interactions between dynamical systems there are two main points of interest,
namely, the degree and the direction of interaction.1
A number of methods have been proposed for
the measurement of phase synchronization2–4 and
of generalized synchronization.5–7 The applicabil-
ity of methods for the detection of the degree
of synchronization between electroencephalographic
(EEG) time series has been demonstrated in a num-
ber of cases, yielding meaningful results for such
different problems as the lateralization of the focal
hemisphere3,7,8 or the detection of changes in the
dynamics of the brain before epileptic seizures.3,9–11
In contrast, directionality measures have only been
applied sparsely to EEG time series, mostly to inves-
tigate the propagation of epileptic seizures from
the focal area to other brain regions.12–16 To our
knowledge, these measures have not been used to
investigate spatio-temporal interactions between the
epileptic focus and other brain regions during the
seizure-free interval.

In the present work, two measures for
directionality, one based on the concept of phase
synchronization and one based on the concept of gen-
eralized synchronization, will be investigated with
regard to their suitability to characterize driver-
responder relationships in coupled model systems17
and in EEG recordings from epilepsy patients. A
question of particular interest is whether an inter-
action between the epileptic focus and other brain
regions in terms of a driver-responder relationship
can be found during the seizure-free period using
these directionality measures.

This paper is organized as follows: In Sec. 2 we
will introduce the measures of directionality used in
this study. In Sec. 3, the results obtained when apply-
ing these measures to exemplary model systems will
be shown. We will demonstrate that the measures
may not be suitable for arbitrary time series, and we

∗Please refer to Sec. 4 for an exact definition of the seizure-free period.
will define certain conditions to be met by the systems under investigation. In the fourth section, an application to the intracranial EEG of an epilepsy patient recorded during the seizure-free interval will be shown. We will demonstrate that one of the directionality measures is suitable to detect a local driving of certain brain structures which affects the medial temporal lobes in both brain hemispheres and which is likely to represent the driving influence of the epileptic focus that is present even during the seizure-free period.

2. Methods

2.1. Phase synchronization

2.1.1. Directionality index

In order to detect directionality of coupling between two dynamical systems Rosenblum and Pikovsky\(^4\) proposed an approach that is based on modeling the phase dynamics. This approach requires the phases to be extracted from the two respective time series \(s_1(t)\) and \(s_2(t)\), where \(s_1(t) = k \cdot \Delta t, k = 1, \ldots, N\), \(\Delta t\) being the sampling interval. Here we use two different techniques to obtain the phase information.

The first technique is based on the analytic signal approach.\(^18\)\(^19\) Given a time series \(s(t)\), an instantaneous phase is obtained from

\[
\phi(t) = \arctan \frac{\Im W(t)}{\Re W(t)},
\]

where \(\Im W(t)\) and \(\Re W(t)\) are the Hilbert transform of the time series \(s(t)\), and \(\phi\) denotes the Cauchy principal value of the integral. An important property of the analytic signal approach is that the instantaneous phase \(\phi(t)\) always relates to the predominant frequency in the Fourier spectrum\(^20\) which may be subject to fluctuations in the time series. An extraction of phase information that automatically adapts to the main rhythm may be advantageous particularly when analyzing nonstationary signals such as the EEG.

The second technique is based on the wavelet transform and is frequency-selective. Here, the phase is defined as

\[
\phi(t) = \arctan \frac{\text{Im} W(t)}{\text{Re} W(t)},
\]

where \(W(t)\) denotes the wavelet coefficient

\[
W(t) = \int_{-\infty}^{\infty} \mu(t - \tau)s(\tau)d\tau
\]

of a Morlet wavelet

\[
\mu(t) = \left(e^{i\omega_0t} - e^{-\frac{t^2}{2\sigma^2}}\right)
\]

with center frequency \(\omega_0\). Defining the band width \(\Delta\omega\) using frequencies for which half of the power is filtered out, one obtains \(\sigma\) as

\[
\sigma = \frac{2\sqrt{\ln 2}}{\Delta\omega}
\]

When using either of these techniques, the phases \(\{\phi_1,\phi_2(t_1)\}\) extracted from the time series \(\{s_1, s_2(t_1)\}\) are confined to the interval \([0, 2\pi]\)^b and have to be unwrapped. One then considers their increments:

\[
\Delta_1,2(k) = \phi_1(t_k + \tau) - \phi_2(t_k).
\]

The constant \(\tau\) should be chosen as \(\tau = \min(T_1, T_2)\), where \(T_1\) and \(T_2\) denote the mean period of oscillation of the first and the second system, respectively.\(^21\) The increments of the phases are then considered as being generated by some noisy map:

\[
\Delta_{1,2}(k) = F_{1,2}[\phi_1(k), \phi_2(k) + \eta_{1,2}(k)].
\]

The dependencies of \(\Delta\) on the phases are modeled by approximating (in the least squares sense) \(F_{1,2}\) using a finite 2-D Fourier series:

\[
F_{1,2}(\phi_1, \phi_2, k) = \sum_{n,m} A_{n,m} e^{in\phi_1 + im\phi_2}
\]

The next step is to quantify the cross-dependencies of the systems via the coefficients \(c_{1,2}\) defined as:

\[
c_{1,2}^2 = \int_0^{2\pi} \int_0^{2\pi} \left(\frac{\partial F_{1,2}}{\partial \phi_1}\right)^2 d\phi_1 d\phi_2.
\]

These integrals can be solved analytically,\(^22\) yielding

\[
c_1 = \sum_{m,l} A_{m,l}^2, \quad c_2 = \sum_{m,l} \Im A_{m,l}^2
\]

In this study we followed Rosenblum and Pikovsky\(^4\) and used the following combinations of

\(^{b}\)While the arctan function is originally defined on \((-\pi/2, \pi/2)\), knowledge of the polarities of \(s(t)\) and \(\mathfrak{s}(t)\) allows a redefinition that yields values in \([0, 2\pi]\).

coefficients to define $F_{1,2}$ as functions of $\phi_1$ and $\phi_2$ (see Eq. (9)): $|l| \leq 3$ for $m = 0$, $|m| \leq 3$ for $l = 0$, and $m = l = 1$. Finally, the directionality of coupling is quantified by

$$d^{1,2} = \frac{c_2 - c_1}{c_2 + c_1}$$

(12)

The directionality index $d^{(1,2)}$ is confined to the interval $[-1, 1]$ and attains positive (negative) values if the first (second) system has a stronger influence on the other system than vice versa. In case of a symmetric coupling, $d^{(1,2)} = 0$ regardless of the degree of synchronization between the systems.

### 2.2. Generalized synchronization

Generalized synchronization is characterized by the existence of some functional relationship between the states of the dynamical systems.\(^{25}\) The first step toward the investigation of generalized synchronization requires the reconstruction of the respective state spaces of the systems from their time series, e.g. by using the method of time delay embedding:\(^{24}\)

Given time series $\{s_{1,1}(t) = s_{1,2}\}$, the state spaces of the systems 1 or 2 are reconstructed by multidimensional vectors $\vec{x}_{1,2}^z$,

$$\vec{x}_{1,2}^z = \left(\vec{x}_{1,2}, \vec{x}_{1,2}^{-1}, \vec{x}_{1,2}^{-2}, \ldots, \vec{x}_{1,2}^{-m}\right),$$

(13)

where $m$ is the embedding dimension and $z$ the time delay. These parameters have to be chosen appropriately, in particular when studying systems with unknown underlying dynamics. When analyzing noisy time series, the concept of a functional relationship may not be appropriate. For this reason we herein rely on the concept of nonlinear interdependence\(^7\) to measure generalized synchronization. Consider two vectors $\vec{x}_{1,2}^z$ in the respective state spaces of the systems 1 and 2 at time $j$. Let the $r$ nearest neighbors of $\vec{x}_{1}^z$ be denoted by $\vec{x}_{1}^z(i)$, $i = 1, \ldots, r$. The systems are considered to be interdependent if for any $j$ the mean squared distance between $\vec{x}_{1}^z$ and its $r$ conditioned neighbors $\vec{x}_{1}^z(i)$ is small compared to the mean squared distance:

$$R'(2) = \frac{1}{M} \sum_{k=1}^{M} (\vec{x}_{2} - \vec{x}_{2}^z)^2$$

(14)

between $\vec{x}_{2}^z$ and all $M$ vectors in its reconstructed state space. With the mean squared distance between the $j$th vector and its $r$ conditioned neighbors in the second system being

$$R_j'(2) = \frac{1}{r} \sum_{k=1}^{r} (\vec{x}_{2} - \vec{x}_{2}^z(i))^2,$$

(15)

one can define as a measure for interdependence:

$$H_r'(2) = \frac{1}{M} \sum_{j=1}^{M} \log \left( \frac{R'(2)}{R_j'(2)} \right).$$

(16)

$H_r'(2) \in R^+_0$, $R^+_0$ being the set of positive real numbers. Note that $H_r'(2)$ depends on the number of nearest neighbors, $r$, in a nonlinear fashion. For independent systems $R'(2) = R'(2)1$ and $H_r'(2) = 0$. In contrast, if the systems are interdependent $R'(2) \gg R'(2)1$ and $H_r'(2) > 0$. $H_r'(2)$ is defined in complete analogy. As an asymmetrical measure for directionality, we use

$$H'_r = \frac{H_r'(1) - H_r'(2)}{2}.$$ 

(17)

$H'_r$ is not bounded, but by definition it will attain positive values if system 1 drives system 2 and negative values for the opposite case. In our applications we use $R' = H'_r$ with $r = 6$.

### 3. Properties of the Directionality Measures

In this section, we investigate important properties of the directionality measures $d^{(1,2)}$ and $H_r$. studying unidirectionally coupled model systems where the first system drives the second. We here restrict ourselves to the analytic signal approach when modeling the phases. We focus on the detectability of the coupling direction and on the robustness against measurement noise.

We consider two diffusively coupled Rössler oscillators:\(^{26}\)

$$\dot{x}_{1,2} = -\omega_1 x_{1,2} - z_{1,2} + \epsilon_1 (x_{2,1} - x_{1,2}),$$

$$\dot{y}_{1,2} = \omega_1 z_{1,2} + 0.165 y_{1,2},$$

$$\dot{z}_{1,2} = 0.2 + z_{1,2} (x_{1,2} - 10).$$

(18)

The equations of motion were integrated using a fourth order Runge-Kutta algorithm with a step size of $dt = 0.05$. The first 10,000 data points were discarded to let transients die out. Using random initial conditions within a sphere with a radius of 0.5 centered at $(1, 1, 1)$ we generated 20 time series (4096 data points; $x$-coordinates of the systems) and varied the coupling strength $\epsilon_1$ ($\epsilon_2 = 0$ since the second
system is driven by the first one), the mismatch of
the natural frequencies $\omega_1, \omega_2$, as well as the level
of noise contamination.

When the systems are uncoupled the directionality
measures are expected to attain values around
zero. When increasing the coupling strength the
measures should increase in step with the growing
influence of the driver on the responder. When the
systems begin to synchronize the dynamics of the
responder adapts to the dynamics of the driver. This
renders the detection of the influence of the driver
on the responder more difficult and should result in
decreased values of the measures. Finally the fully
synchronized state is reached where the dynamics of
both systems are identical. Here, a detection of the
direction of coupling is no longer possible and the
measures should reach values around zero.

In Fig. 1 we show the dependence of $d^{(1,2)}$ on
$\epsilon_1$ which was varied between 0 and 1 in steps
of 0.05. The natural frequencies of the oscillators
were chosen as $\omega_1 = 0.89$ and $\omega_2 = 0.8$. Qual-
itatively, the expected behavior can be observed
except that $d^{(1,2)} \neq 0$ for uncoupled systems which
can be attributed to the mismatch of the natural
frequencies.

The result for the other directionality measure
$H_-$ is shown in Fig. 2 for two different time delays $z$.
For an underestimated time delay ($z = 1$) $H_-$ erroneously indicates that system 2 is driving sys-
tem 1. In contrast, for an appropriately chosen $z$
(e.g. from the first zero-crossing of the autocorrela-
tion function) the expected dependence of $H_-$ on
$\epsilon_1$ is observed. Note that $H_-$ is not affected
by the mismatch of the natural frequencies. These find-
ings clearly indicate that a proper unfolding of the
dynamics in state space (i.e., a proper choice of both
the embedding dimension $m$ and the time delay $z$) is
mandatory. When analyzing time series from systems
with unknown properties this crucial dependence of
$H_-$ on the embedding parameter may limit the appli-
cability of this directionality measure.

We have already noted that the phase-based
directionality measure $d^{(1,2)}$ (but not $H_-$) is affected
by the mismatch of the natural frequencies $\Delta \omega =
\omega_2 - \omega_1$. In order to evaluate this influence in more
detail we again studied uncoupled Rössler oscilla-
tors with $\omega_1 = 0.9$ while $\omega_2$ was increased from 0.6
to 1.2 in steps of 0.01. The results for $d^{(1,2)}$ are
shown in Fig. 3. For small frequency mismatches
($-0.1 < \Delta \omega < 0.1$), $d^{(1,2)}$ indicates that the sys-
tem with a higher natural frequency drives the other
system. For $|\Delta \omega| > 0.1$ there is no clear tendency
but the dependence on the frequencies remains. In
contrast, $H_-$ fluctuates around zero indicating that
this directionality measure is not affected by the fre-
quency mismatch (cf. Fig. 4).

In order to evaluate the robustness of the direc-
tionality measures against contamination of the time
series with measurement noise, we studied the oscil-
lators with fixed natural frequencies ($\omega_1 = 0.89$
and $\omega_2 = 0.8$) and added Gaussian white noise

\begin{figure}[h]
  \centering
  \includegraphics[width=\textwidth]{fig1.png}
  \caption{Influence of the coupling strength $\epsilon_1$ on the
directionality index $d^{(1,2)}$ for coupled Rössler oscillators. System 1 is driving system 2. Means and standard devia-
tions obtained from 20 realizations of the $x$-components.}
\end{figure}
Measuring the Directionality of Coupling

Fig. 3. Influence of frequency detuning $\Delta \omega$ of the uncoupled Rössler oscillators on the directionality measure $d^{(1,2)}$.

Fig. 4. Same as Fig. 3 but for the directionality measure $H_{-}$.

Fig. 5. Robustness of the normalized directionality measures $\tilde{d}^{(1,2)}$ and $\tilde{H}_{-}$ against measurement noise. NSR denotes the noise-to-signal ratio.

of increasing amplitude (quantified by noise to signal rate $\text{NSR} = \frac{\sigma_{\text{noise}}}{\sigma_{\text{signal}}}$) to the time series $\sigma_{\text{noise}}$ and $\sigma_{\text{signal}}$ denote the standard deviations of the noise and of the uncontaminated time series, respectively. We here used different coupling strengths ($\epsilon_2 = 0; \epsilon_1 = 0.1$ for $H_{-}; \epsilon_1 = 0.15$ for $d^{(1,2)}$) since the measures depended differentially on the coupling strength. The respective values for $\epsilon_1$ were chosen such that each measure attained its maximum value at them, without presence of noise (cf. Figs. 1 and 2).

In Fig. 5 we present the dependence of the normalized measures (relative to their value at $\text{NSR} = 0$) on the noise to signal ratio $\text{NSR}$. Both measures are robust against low amplitude noise ($\text{NSR} \leq 0.1$). In the intermediate range of noise amplitudes ($0.1 \leq \text{NSR} \leq 0.2$) the phase-based directionality index exhibits a high variance which renders a reliable detection of the direction of coupling rather difficult. In contrast, the state-space based directionality index exhibits a clearly smaller spread. For $\text{NSR} > 0.2$ both measures fail to detect any direction of coupling.

Summarizing this section we conclude that both directionality measures allow to detect the direction of coupling. However, our findings also indicate that precautions have to be taken to avoid misinterpretations when analyzing the dynamics of unknown systems. As a general rule, the noise contamination of the time series should be as low as possible which may require filtering of the data. When using the state-space based approach the appropriate choice of the embedding parameters is crucial. For the phase-based approach we observed a strong influence of the system characteristic natural frequency which requires an appropriate analysis of the phases. When using adaptive phase extraction techniques (such as the Hilbert transform) it must be ensured that an apparent indication of directionality is not trivially explained by different spectral properties of the time series. A frequency band selective extraction of the phase (e.g. using the wavelet transform) does not suffer from this shortcoming but it bears the risk of discarding meaningful information.
4. An Application to EEG: Measuring Focal Driving in the Epileptic Brain

An important and yet unanswered question in epileptology is whether pathological interactions between the seizure generating area of the brain (epileptic focus) and remote areas can be identified during seizure-free periods from patients with focal epilepsy. The epileptic focus is usually identified by recording the seizure onset using multichannel electroencephalography (EEG). The detection of interactions in the sense of a driver-responder relationship could help to further improve understanding of the epileptogenic process. A question of particular interest is whether these pathological interactions are locally restricted to the immediate surroundings of the focus or whether they also involve remote brain regions. The directional character of the measures is crucial here and is not provided by, e.g., measures quantifying the degree of synchronization.

In the following we present findings obtained from applying the measures of directionality (see Sec. 2) to intracranial EEG recordings from a patient with mesial temporal lobe epilepsy and a well-defined epileptogenic focus. Magnetic resonance imaging yielded a left hippocampal sclerosis, invasive recording of the seizure onset confirmed this area to be the seizure onset zone. After neurosurgical resection of the hippocampal formation (selective amygdalo-hippocampectomy) the patient was seizure-free so the focus can be assumed to be located within the resected area. We restricted our analysis to depth EEG recordings from the seizure-free (interictal) interval (3 segments of different duration (range 40–60 min) that were selected such that each segment started at least 1 h after a seizure and ended at least 4 h before a seizure). The total recording time amounted to 143 min. The EEG was recorded via intrahippocampal depth electrodes (Fig. 6), each equipped with 10 cylindrical contacts (diameter: 2.5 mm, intercontact distance: 4 mm), using an average common reference. These electrodes were implanted stereotactically in the medial temporal lobes via the longitudinal axis of the hippocampus using an occipital approach with the amygdala as target for the most anterior electrode contact. After neurosurgical implantation, the correct placement of the electrodes was verified by magnetic resonance imaging. EEG recordings were performed at a sampling frequency of 173.61 Hz using a 12 bit analog to digital (A/D) converter and the data was band-pass filtered from 0.5 to 85 Hz (12 dB/oct.). An exemplary interictal EEG recording of 15 s. duration is shown in Fig. 7. Recordings from depth electrodes have an excellent noise to signal ratio and are not affected by movement artifacts.

We performed the following steps of analysis. First, we divided the EEG time series into non-overlapping segments of 23.6 s duration (corresponding to 4096 data points) that allowed us to calculate the measures for directionality for each combination of pairs of electrode contacts in a moving window fashion. Second, the information content of the resulting measure profiles was then compressed by calculating the temporal average (i.e., over all windows) separately for each combination of electrode contacts. Using these data, we set up a directionality matrix $M(\Gamma)$ for each measure $\Gamma$. Figure 8 shows the matrix for the phase-based directionality index $d(1,2)$, where we used the analytic signal approach to obtain the phase information.

Since $d(1,2) = -d(2,1)$, the matrix is antisymmetric. A matrix entry $M(d(1,2))_{ij}$ in the $i$-th row and in the $j$-th column attains positive values if the system corresponding to the column index is driving the system corresponding to the row index. In Fig. 8 the structure recorded at the fourth and fifth electrode contact in the left hemisphere appears to drive both the left and right medial temporal regions of the brain. Visual analysis of the raw EEG data including seizure activity by a clinician expert confirmed that the first signs of seizure activity were...
Fig. 7. Exemplary EEG recording from the seizure-free interval. Upper part: recordings from the left medial temporal lobe; lower part: recordings from the right medial temporal lobe. See Fig. 6 for electrode contact labeling.

Fig. 8. Directionality matrix $M(1,2)$ obtained from modeling the phase dynamics of the EEG using the Hilbert transform. Each color coded matrix entry represents the temporal average of $d(1,2)$ for each combination of electrode contacts.

always restricted to these two contacts. This finding supports the hypothesis that this local driving structure indeed corresponds to the epileptic focus. As already stated at the end of Sec. 3, however, the interpretation of such findings can be misleading. In order to ensure that the observed effects can not be trivially explained by differences in the spectral properties of the measured signals, we performed a moving window spectral analysis of the EEG time series using the same window length as before and calculated the mean spectral power over time for each Fourier component. In order to quantify possible differences in the power spectra between the time series, we then compared the Fourier spectra from the driving contacts with the mean over all contacts.

As shown in Fig. 9, the relative spectral density of the EEG recordings from the driving contacts is higher than the average relative spectral density over all recording sites in the frequency band between 8 and 40Hz (i.e., in the $\alpha$, $\beta$ and $\gamma$ band). Since our model investigations have shown that frequency mismatches may cause a spurious indication of directionality even in the case of uncoupled systems, we performed a band-selective calculation of the directionality index $d(1,2)$. In order to obtain the phase information we used a wavelet-based approach (see Sec. 2.1.1) with the center frequency $\omega_0$ and bandwidth of the Morlet wavelet adapted to match the EEG bands, i.e., the $\delta$ band (0.5–4Hz), the $\theta$ band (4–8Hz), the $\alpha$ band (8–13Hz), the $\beta_1$ band (13–20Hz), the $\beta_2$ band (20–30Hz), and the $\gamma$ band
Fig. 9. Normalized spectral density (average over all electrode contacts) of EEG and spectral power of EEG from contacts 4 and 5 in the left hemisphere.

Fig. 10. Same as Fig. 8 but using the wavelet transform with center frequency $\omega_1$ in the $\delta$ band.

Fig. 11. Same as Fig. 8 but using the wavelet transform with center frequency $\omega_0$ in the $\theta$ band.

(30–49 Hz) at full width half maximum. No clear-cut effects could be observed in the frequency bands above 8 Hz. In contrast, the frequency-selective directionality matrices $M(\delta^{(1,2)})$ for the $\delta$ and $\theta$ bands (cf. Figs. 10 and 11) exhibit a spatial distribution of driving effects that closely resembles the one obtained from the adaptive phase definition based on the Hilbert transform.

To allow a better comparison between the adaptive and the frequency-specific approaches we here define the mean local driving per electrode site as the average over all entries for each column of the matrix $M$. Figure 12 shows the mean local driving values of each electrode contact for the two frequency-selective and the adaptive phase extractions. These findings indicate that the local information obtained from the adaptive approach is composed of the local information obtained from the frequency-specific (i.e., $\delta$ and $\theta$ band) approaches. The fact that our findings are similar independently of the phase-extraction method indicates that the observed phenomenon of a local driving cannot trivially be explained by a frequency mismatch between the EEG time series from different recording sites (cf. Fig. 3). For the calculation of the state-space based directionality index $H_\rightarrow$, we used an embedding dimension $m = 10$ for the state space reconstruction of the EEG time series. The time delay $z$ was chosen as the mean decorrelation time, i.e., the average of the first zero crossing of the autocorrelation functions from all EEG segments from all electrode contacts. This value amounted to 160 msec corresponding to 27 data points. Figure 13 shows the directionality matrix $M(H_\rightarrow)$. The results obtained here clearly differ from those obtained from the phase-dynamics approach, particularly no driving region can be identified.

The application of nonlinear directionality measures to intracranial EEG recordings from an exemplary patient has shown that the phase-based directionality index is capable of identifying a distinct region that drives the surrounding brain regions both
on the side of the epileptic focus and in the opposite hemisphere during the seizure-free interval. This driving is primarily observed in the $\delta$ and $\vartheta$ band. The fact that the first electrographical signs of seizure activity are found in the same contacts that exhibit the local driving makes it reasonable to assume that the observed local driving indeed reflects an interaction of the epileptic focus with other brain regions that is otherwise not visible in the raw EEG signal. Remarkably, the driving influence of the presumed epileptic focus is not restricted to its immediate surroundings, but extends to remote areas in the contralateral hemisphere, which supports the notion of an epileptic network whose interactions interictally extend over large regions of the brain. Further studies on large patient collectives using continuous multi-day recordings are necessary to confirm this finding and could contribute to a better understanding of the dynamics of the interictal state and its role in ictogenesis.

From our first preliminary findings it appears that the nonlinear interdependency measure $H_{-\tau}$ was not suitable to reflect any dynamical interaction possibly related to the underlying pathology. For this measure, the sensitive dependence on the embedding parameters may play an important role. It is also conceivable that the choice of other, optimized parameters for $H_{-\tau}$ (e.g., the time delay of the embedding) would lead to better results.

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